Are the Highest-Redshift Quasars Magnified by Intervening Gravitational Lenses?

J. Stuart B. Wyithe and Abraham Loeb

Astronomy Dept., Harvard University, 60 Garden Street, Cambridge, MA 02138, USA

The Sloan digital sky survey (SDSS) has recently discovered exceptionally bright quasars[1] with redshifts of up to 6.28. Naively, these observations imply the existence of black holes with masses in excess of a few billion solar masses only a billion years after the big bang. Moreover the inferred luminosities of these bright quasars are systematically higher than expected from the survey selection criteria. Here we explain these puzzling results by the inevitable phenomenon of gravitational lensing. We find that up to a third of the SDSS quasars at $z \sim 6$ are likely to have their intrinsic flux magnified by a factor $\gtrsim 10$ due to lensing by intervening galaxies.

The $z \sim 6$ quasars appear to be as bright as 3C273, the brightest quasar in the local universe. Even if these accreting black holes shine near their maximum (Eddington) luminosity, their observed fluxes require the assembly of a mass $\gtrsim 3 \times 10^9 M_\odot$ in a relativistic potential well when the age of the universe was only $5 - 10\%$ of its current value, and so they challenge models for early structure formation[2,3]. The prominence of supermassive black holes in the early universe could have important implications for the re-ionization of the primordial hydrogen[4,5] at $z \gtrsim 6$. It is currently unknown whether the cosmic neutral hydrogen, a cold remnant from the big bang, was re-ionized by star light or by quasars[6,7].

The first step toward a resolution of these issues was made with the observation of 4 very high-redshift quasars[8,1] (with $z \gtrsim 5.8$; SDSS 1044-0125 was later found[9] to have $z = 5.73$), and a catalog of 39 quasars[10,11] with a median redshift of $z \sim 4.3$ ($3.6 < z < 5.0$). These samples were selected in the SDSS photometric magnitude system to have magnitudes $z^* < 20.2$ and colors $i^* - z^* > 2.2$ at $z \gtrsim 5.8$, and $i^* < 20.0$ at $z \sim 4.3$. The quasar luminosity function (number per comoving volume per unit luminosity) is very well determined[12] at redshifts $z \lesssim 3$, having a characteristic break with a slope at the bright end of -3.43 that does not evolve with redshift. However, the SDSS sample at $z \sim 4.3$ shows a bright–end slope of -2.58, significantly flatter than the low redshift value, and implying the existence of many more luminous quasars[11]. On the other hand the SDSS sample of $z \gtrsim 5.8$ quasars is consistent[1] with the steep slope (-3.43) found at $z < 3$.

Assuming a steep bright–end slope of -3.43, the measured luminosities of the four $z \gtrsim 5.8$ quasars present a new puzzle. If the cumulative probability of the inferred absolute magnitudes (denoted by dots in Figure 1) is compared with the expected distribution of absolute magnitudes for the $z \gtrsim 5.8$ sample, one finds that while the slope of the observed and expected distributions are consistent, the quasars are systematically brighter than expected. We have computed the probability of observing a quasar in the $z \gtrsim 5.8$ survey with absolute magnitude greater than M_{1450} (AB magnitude of the continuum at rest-frame 1450Å). The co-moving space density of quasars was assumed to decline with redshift[11] in proportion to $10^{-0.48z}$, and the probability that a quasar with continuum magnitude M_{1450} and redshift z was selected into the survey was taken from the published survey selection function[1]. The resulting cumulative probability is plotted in Figure 1. A Kolmogorov-Smirnov test shows the observations to be inconsistent with this distribution at the 95% level. On the other hand, if the flux of one or more of the quasars was overestimated by a factor $\gtrsim 2$ then this inconsistency is removed. In the following, we show that the required overestimation is a natural consequence of gravitational lensing by foreground galaxies. Throughout this *Letter* we adopt a cosmology described by density parameters $\Omega_m = 0.35$ in matter and $\Omega_\Lambda = 0.65$ in a cosmological constant, and a Hubble constant of $H_0 = 65\,\mathrm{km\,sec^{-1}\,Mpc^{-1}}$.

The quasar luminosity function at $z \lesssim 3$ is well described by a double power-law whose shape does not evolve with redshift[12],

$$\phi(L,z) = \frac{\phi_\star/L_\star(z)}{[L/L_\star(z)]^{\beta_l} + [L/L_\star(z)]^{\beta_h}}. \tag{1}$$

The observed evolution of the break luminosity $L_\star$ is well-described by the dependence[6]

$$L_\star(z) = L_\star(0)(1+z)^{-(1+\alpha_q)} e^{\zeta z} \frac{1+e^{\xi z_\star}}{e^{\xi z} + e^{\xi z_\star}}. \tag{2}$$

We find that an intrinsic luminosity function having the parameters $\phi_\star = 624\,\mathrm{Gpc^{-3}}$, $\beta_l = 1.64$, $\beta_h = 3.43$, $L_\star(0) = 1.5 \times 10^{11}\,L_\odot$, $\alpha_q = -0.5$, $z_\star = 1.45$, $\xi = 2.9$, $\zeta = 2.7$ and the inclusion of gravitational lensing (described below) adequately describes three observables, namely the luminosity function at $z \lesssim 3$, and the number density of quasars with absolute B-magnitude $M_B < -26$ at $z \sim 4.3$ and $M_B < -27.6$ at $z \sim 6.0$. The parameter α_q is the slope assumed for the typical quasar continuum $L(\nu) \propto L^{\alpha_q}$. We are interested in the number of quasars with luminosities higher than the limiting magnitude $z^*_{\rm lim} = 20.2$, which is $N(>L_{\rm lim}, z) = \int_{L_{\rm lim}}^{\infty} dL\, \phi(L,z)$ where $L_{\rm lim}$ is the luminosity of a quasar at redshift z corresponding to an apparent magnitude $z^*_{\rm lim}$. $L_{\rm lim}$ was determined from $z^*_{\rm lim}$ using a luminosity distance and a k-correction computed from a model quasar spectrum including the mean absorption by the intergalactic medium[13,14].

The magnification of the intrinsic quasar flux through gravitational lensing offers an attractive explanation for the discrepant $z \gtrsim 5.8$ luminosities. To illustrate this point, we consider a fictitious gravitational lens that always produces a magnification of $\mu = 4$ for the sum of multiple images [the average value for a singular isothermal sphere (SIS)] but $\mu = 1$ otherwise. Surveys for quasars at $z < 3$ have limiting magnitudes fainter than the break magnitude ($m_B \sim 19$). The probability that a quasar at $z \sim 2$ will be multiply imaged[16] is

~ 0.002. However a survey for quasars to a limit $L_{\rm lim}$ will find a number of lensed sources that is larger by a bias factor of $N(< L_{\rm lim}/\mu, z)/N(< L_{\rm lim}, z)$. At $z = 2$, $L_{\rm lim}(z) \ll L_{\star}(z)$ and for $\beta_l = 1.6$ the magnification bias factor is ~ 2.3, resulting in a lens fraction of ~ 0.005. At $z = 6$ the probability that a quasar will be multiply imaged is ~ 0.008. Furthermore, the limiting magnitude of the $z \gtrsim 5.8$ survey is significantly brighter than the break magnitude and so $\beta_h = 3.4$ and the bias factor rises to ~ 28. Under these circumstances, the lens fraction rises to ~ 0.22. If the bright end slope is shallower at high redshift, say $\beta_h = 2.6$, then the bias is ~ 9, and the lens fraction is ~ 0.07. These simple arguments are consistent with previous estimates of the lensing rate at high redshift[17] and demonstrate that lensing has a strong effect on observations of the bright SDSS quasars at $z \gtrsim 5.8$.

To find the magnification bias more accurately, we have computed the probability distributions $\frac{dP_{\rm sing}}{d\mu}$ and $\frac{dP_{\rm mult}}{d\mu_{\rm tot}}$ for the magnification μ of randomly positioned singly-imaged sources, and for the sum of magnifications $\mu_{\rm tot}$ of randomly positioned multiply-imaged sources due to gravitational lensing by foreground galaxies. We assume that the lens galaxies have a constant co-moving density [as the lensing rate for an evolving (Press–Schechter) population of lenses differs only by $\lesssim 10\%$ from this case[17]] and are primarily early type (E/S0) SIS galaxies[18] whose population is described by a Schechter function with parameters[19] $n_{\star} = 0.27 \times 10^{-2}\,{\rm Mpc}^{-3}$ and $\alpha_s = -0.5$. We assume the Faber-Jackson relation $(L_g/L_{g\star}) = (\sigma_g/\sigma_{\star})^4$ where σ_g is the velocity dispersion of the lens galaxy, with $\sigma_{\star} = 220\,{\rm km\,sec}^{-1}$ and a dark matter velocity dispersion that equals the stellar velocity dispersion[18]. We ignore dust extinction by the lens galaxy, which mainly arises in the much rarer spiral galaxy lenses. Potential lens galaxies must not be detectable in the survey data used to select the objects. Galaxies having $i^* < 22.2$ (around 30% of the potential lens population) are not considered part of the lens population. To compute i^* for a galaxy having velocity dispersion σ at redshift z we use $L_{g\star}$ from the 2dF early type galaxy luminosity function[19], the Faber-Jackson relation, color transformations and a

k-correction[20,21], and the evolution of the rest-frame B-band mass-to-light ratio[22].

Our lens model includes microlensing by the population of galactic stars which is modeled as a de Vaucouleurs profile of point masses embedded in the overall SIS mass distribution. The surface mass density in stars for galaxies at $z = 0$ is normalized so that the total cosmological density parameter of stars[23] equals 0.005. At $z > 0$ the total mass density in stars is assumed to be proportional to the cumulative star-formation history[24,25]. The parameters of the de Vaucouleurs profiles are taken from a study of the fundamental plane[26], the microlens mass is chosen as $0.1M_\odot$ and the source size as 10^{15}cm (corresponding to ten Schwarzschild radii of a $3 \times 10^8 M_\odot$ black hole). The probabilities $\frac{dP_{\rm sing}}{d\mu}$ and $\frac{dP_{\rm mult}}{d\mu_{\rm tot}}$ were computed by combining numerical magnification maps with the distribution of microlensing optical depth and shear along lensed lines of sight, and the distribution $\left[\tau_{\rm mult}\frac{dP_{\rm mult}}{d\mu} + (1-\tau_{\rm mult})\frac{dP_{\rm sing}}{d\mu}\right]$ was normalized to have unit mean.

The fraction of sources which are multiply imaged due to gravitational lensing is

$$F_{\rm MI}(z) = \frac{\int_0^\infty d\mu' \tau_{\rm mult}\frac{dP_{\rm mult}}{d\mu'} N(> \frac{L_{\rm lim}}{\mu'}, z)}{\int_0^\infty d\mu' \left[\tau_{\rm mult}\frac{dP_{\rm mult}}{d\mu'} + (1-\tau_{\rm mult})\frac{dP_{\rm sing}}{d\mu'}\right] N(> \frac{L_{\rm lim}}{\mu'}, z)}, \quad (3)$$

where $\tau_{\rm mult} = 0.0059$ is the multiple image cross-section[15]. We find a value of $F_{\rm MI} \sim 0.30$ for the color-selected, flux-limited $z \gtrsim 5.8$ sample. This value is higher by two orders of magnitude than the lens fraction at low redshifts and demonstrates that lensing must already be considered in a sample with only 4 objects. We find that consideration of microlensing increases the the multiple imaging rate by $\sim 15\%$. Magnification bias also affects quasars that are not multiply imaged, and we find that the mean number of quasars in the survey is increased a factor of ~ 1.5. We therefore predict an enhanced angular correlation on the sky between $z \sim 6$ quasars and foreground galaxies.

A sub arc–second resolution K-band image has been obtained for the $z = 5.80$ quasar[1], and it was found to be an unresolved point source. To our knowledge this is the only $z \gtrsim 5.8$ quasar for which sub arc–second resolution data is currently available. However a program to image these quasars with HST which will determine the multiple-image fraction, is expected to begin within the coming year (X. Fan private communication). Note though that single image quasars might still be magnified by a factor of ~ 2.

We have computed the distribution of magnifications observed for a sample of quasars brighter than $L_{\rm lim}$ at redshift z,

$$\frac{dP}{d\mu_{\rm obs}} = \frac{\left[\tau_{\rm mult}\frac{dP_{\rm mult}}{d\mu}|_{\mu=\mu_{\rm obs}} + (1-\tau_{\rm mult})\frac{dP_{\rm sing}}{d\mu}|_{\mu=\mu_{\rm obs}}\right] N(>\frac{L_{\rm lim}}{\mu_{\rm obs}})}{\int_0^\infty d\mu' \left[\tau_{\rm mult}\frac{dP_{\rm mult}}{d\mu}|_{\mu=\mu'} + (1-\tau_{\rm mult})\frac{dP_{\rm sing}}{d\mu}|_{\mu=\mu'}\right] N(>\frac{L_{\rm lim}}{\mu'})}. \quad (4)$$

In Figure 2 we show the probability that the magnification of a quasar is higher than $\mu_{\rm obs}$, assuming that the quasar belongs to a sample at a redshift $z \sim 6$ with the SDSS magnitude limit of $z^* < 20.2$. The plotted distribution is highly skewed; the median magnification is $med(\mu_{obs}) \sim 1.2$ while the mean magnification is as high as $\langle\mu\rangle = 23$. We have also computed the *a-posteriori* values of $F_{\rm MI}$ and $\langle\mu\rangle$ for specific quasars. For SDSS 0836-0054 ($z = 5.82$), SDSS 1306-0356 ($z = 5.99$) and SDSS 1030-0524 ($z = 6.28$) we find $F_{\rm MI} = 0.40$, 0.32 and 0.31, and $\langle\mu\rangle = 50$, 25 and 23, respectively. These results provide a quantitative explanation for the puzzle posed by Figure 1. One or more of these quasars are likely to be highly magnified, placing the data in line with the survey selection function. More importantly, the proliferation of highly magnified, gravitationally–lensed sources means that the effect of lensing must be taken into account when constructing luminosity functions or inferring the luminosity density of quasars at high redshift. Note that naive computation of the luminosity density from the $z \gtrsim 5.8$ sample might overestimate its value by more than an order of magnitude.

While Fan et al. (2001) find that $\beta_h = 3.43$ is consistent with the luminosities of the $z \gtrsim 5.8$ quasars, it is possible that the luminosity function at high redshift is not as steep as $\beta_h = 3.43$. In this case, the magnification bias will not be as large and the mean magnification and fraction of quasars that are multiply imaged will be lower. We have re-computed the lens statistics assuming that the bright end slope is significantly flatter at high redshift. Assuming that $\beta_l = 1.64$ at all redshifts and $\beta_h = 3.43$ for $z < 3$ but $\beta_h = 2.58$ for $z > 3$ (the value found for the $z \sim 4.3$ sample) we inferred similar parameters to describe the observed luminosity function as before [$L_\star(0) = 1.5 \times 10^{11} L_\odot$, $z_\star = 1.6$, $\xi = 3.3$, $\zeta = 2.65$]. Remarkably, the multiple image fraction is still nearly 0.1 in this case.

Finally we note that even though a lens galaxy cannot be detected in the initial survey, its light may still contaminate subsequent deep observations of the Gunn-Peterson trough[27] in the quasar spectrum. The recently published spectra of the highest redshift quasar[5,28] limit the flux in the Gunn-Peterson trough to less than $3 \times 10^{-19}\,\mathrm{erg\,sec^{-1}\,\AA^{-1}}$. We have computed the flux of lens galaxies at redshift z with velocity dispersion σ, and convolved the results with the joint probability distribution for the lens galaxy redshift and velocity dispersion. We find that $\sim 40\%$ of multiple image lens galaxies ($i^* < 22.2$) will contribute flux in the Gunn-Peterson trough above a level of $3 \times 10^{-19}\,\mathrm{erg\,sec^{-1}\,\AA^{-1}}$. For some quasars the contamination of the Gunn-Peterson trough by flux from lens galaxies may limit the ability of deep spectroscopic observations to probe the evolution of the neutral hydrogen fraction during the epoch of reionization.

Correspondence and requests for materials to Abraham Loeb.

REFERENCES

[1]Fan, X., *et al.*, 2001, Survey of z> 5.8 quasars in the Sloan digital sky survey. I. Discovery of three new quasars and the spatial density of luminous quasars at z∼ 6, *Astron. J.* **122**, 2833-2849

[2]Turner, E.L., 1991, Quasars and galaxy formation. I - The Z greater than 4 objects, *Astron. J.* **101**, 5-17

[3]Haiman, Z., & Loeb, A., 2001, What is the highest plausible redshift for quasars, *Astrophys. J.* **503**, 505-517

[4] Barkana, R., & Loeb, A., 2001, In the beginning: the first sources of light and the reionization of the universe, *Phys. Rep.*, **349**, 125-238

[5]Becker, R.H., *et al.*, 2001, Evidence for reionization at $z \sim 6$: Detection of a Gunn-Peterson trough in a $z = 6.28$ quasar, *Astron. J.* **122**, 2850-2857

[6]Madau, P., Haardt, F., Rees, M.J., 1999, Radiative transfer in a clumpy universe. III. The nature of cosmological ionizing sources, *Astrophys. J.* **514**, 648-659

[7]Haiman, Z., & Loeb, A., 1998, Observational signatures of the first quasars, *Astrophys. J.* **503**, 505-517

[8]Fan, X., *et al.*, 2000, Discovery of a luminous z=5.80 quasar from the Sloan digital sky survey, *Astron. J.* **120**, 1167-1174

[9]Djorgovski, S. G.; Castro, S., Stern, D., Mahabal, A.A., 2001, On the Threshold of the Reionization Epoch, *Astrophys. J.* **560**, L5

[10]Fan, X., *et al.*, 2001, High redshift quasars found in the Sloan digital sky survey commissioning data. III. A color selected sample at $i^* < 20$ in the fall equatorial stripe, *Astron. J.* **121**, 31-53

[11]Fan, X., *et al.*, 2001, High redshift quasars found in the Sloan digital sky survey commissioning data. IV. Luminosity function from the fall equatorial sample, *Astron. J.* **121**, 54-65

[12]Pei, Y.C., 1995, The Luminosity function of quasars, *Astrophys. J.* **438**, 623-631

[13]Fan, X., 1999, Simulation of stellar objects in SDSS colour space, *Astron. J.* **117**, 2528-2551

[14]Møller, P., Jakobsen, P., 1990, The Lyman continuum opacity at high redshifts: through the Lyman forest and beyond the Lyman valley, *Astron. Astrophys.* **228**, 299-309

[15]Turner, E.L., Ostriker, J.P., Gott, R., 1984, The statistics of gravitational lenses: The distributions of image angular separations and lens redshifts, *Astrophys. J.* **284**, 1-22

[16]Turner, E.L., 1990, Gravitational lensing limits on the cosmological constant in a flat universe, *Astrophys. J.* **365**, L43-L46

[17]Barkana, R., & Loeb, A., 2000, High-redshift quasars: Their predicted size and surface brightness distributions and their gravitational lensing probability, *Astrophys. J.* **531**, 613-623

[18]Kochanek, 1996, Is there a cosmological constant?, *Astrophys. J.* **466**, 638-659

[19]Madgwick, D.S., *et al.*, 2001, The 2dF galaxy redshift survey: Galaxy luminosity functions per spectral type, astro-ph/0107197

[20]Blanton, M.R., *et al.*, 2001, The luminosity function of galaxies in SDSS commissioning data, *Astron. J.* **121**, 2358-2380

[21]Fukugita, M., Shimasaku, K., Ichikawa, T., 1995, Galaxy colours in various photometric band systems, *Pub. Royal Astron. Soc. Pac.* **107**, 945-958

[22]Koopmans, L.V.E., Treu, T., 2002, The internal structure and formation of early type galaxies: The gravitational-lens system MG2016+112 at z=1.004, *Astrophys. J.* **568**, L5

[23] Fukugita, M., Hogan, C. J., Peebles, P. J. E. 1998, The Cosmic baryon budget, *Astrophys. J.* **503**, 518-530

[24]Hogg, D., 2001, A meta-analysis of cosmic star-formation history, astro-ph/105280

[25]Nagamine, K., Cen, R., Ostriker, J.P., 2000, Luminosity density of galaxies and cosmic star-formation rate from Λ cold dark matter hydrodynamical simulations, *Astrophys. J.* **541**, 25-36

[26]Djorgovski, S., Davis, M., 1987, Fundamental properties of elliptical galaxies, *Astrophys. J.* **313**, 59-68

[27]Gunn, J. E., Peterson, B. A., 1965, On the density of neutral hydrogen in intergalactic space, *Astrophys. J.* **142**, 1633-1641

[28]Pentericci, L., *et al.*, 2001, VLT optical and near-IR observations of the z=6.28 quasar SDSS 1030+0524, astro-ph/0112075

ACKNOWLEDGEMENTS. The authors would like to thank Ed Turner and Josh Winn for helpful discussions. This work was supported in part by grants from the NSF and NASA. J.S.B.W. is supported by a Hubble Fellowship.

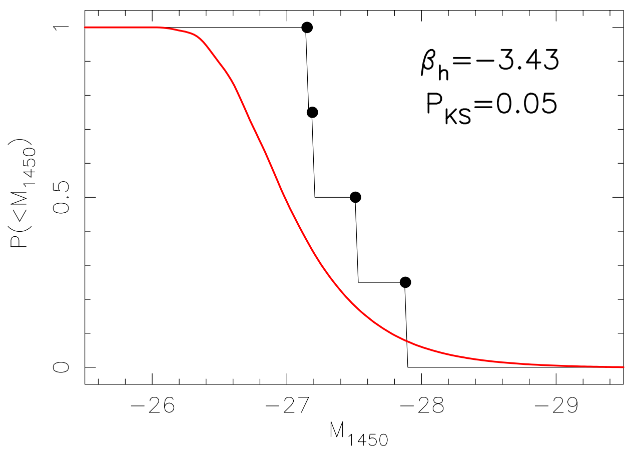

Fig. 1.— The expected and observed cumulative probabilities for the absolute continuum magnitude M_{1450} of the SDSS $z \gtrsim 5.8$ sample. The dots show the histogram for the 4 SDSS high redshift quasars. This is contrasted with the expected distribution obtained from the published survey selection function and a power-law luminosity function $\phi(L, z) \propto L^{-3.43} 10^{-0.48z}$. Note that we calculate the fraction of quasars in the survey brighter than M_{1450} and so the distribution is independent of the normalization against low redshift samples. The observed quasars are systematically brighter than expected, and are formally different from the expected distribution at the 95% level based on a Kolmogorov-Smirnov test.

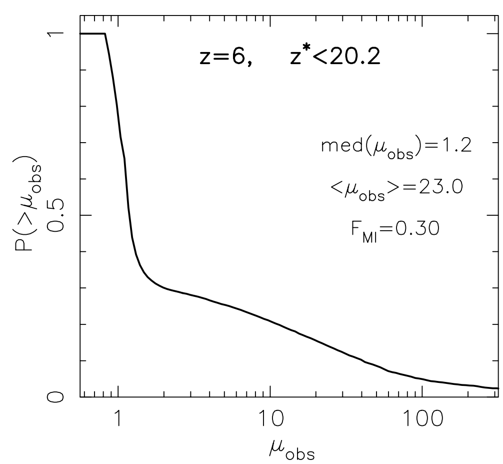

Fig. 2.— The probability of observing a magnification larger than $\mu_{\rm obs}$ for a quasar at a redshift $z = 6$ in a sample with a magnitude limit $z^* < 20.2$. The distribution is highly skewed, having a median of $med(\mu_{obs}) = 1.2$ and a mean of $\langle\mu_{obs}\rangle = 23.0$. The multiple image fraction is $F_{MI} = 0.30$.